Sorghum and Millet Adaptation to Photoperiod, Pest Incidence, and Soil Moisture-Retention Capacity

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Abstract

Three independent factors—photoperiodic response, pest resistance, and soil moisture-retention capacity—frequently combine to determine sorghum and millet yields. The duration and time of occurrence of the different development phases (vegetative, flowering, and fruiting) of a cultivar depend on the planting date and photoperiodic response, in relation to available water and pest incidence. These last two factors are in turn determined by rainfall distribution and the water-holding capacity of a soil. This is demonstrated through a probabilistic model of the climatic period corresponding to the growing period and a model for evaluating the fitting of cultivar cycles based on relative yield, Y/100.

Introduction

There is no apparent relationship between daylength (photoperiod), water-holding capacity, and parasitism but in reality, sorghum and millet yields are determined to a large extent by the combined effect of these factors. This can be illustrated with the help of two models:

- The frequency model of the climatic growing period is a geometrical model that combines the physical characteristics of the soil and atmosphere, and describes this growing period in probabilistic terms of its duration and time of occurrence. The principle of this model was presented at ICRISAT in 1978 at the International Workshop on the Agroclimatological Needs of the Semi-Arid Tropics.
- A model for evaluating the effect on yield of the fitting of cultivar cycles to the statistical characteristics—duration and time of occurrence—of the growing period as established by the frequency model.

The second model is based on the hypothesis that dry-matter (DM) production is a function of the sum of instantaneous values of relative evapotranspiration; i.e. the ratio of actual evapotranspiration to potential evapotranspiration (AET/PET) (Franquin 1980 a):

$$\text{Yield (DM)} = f\left(\int_{t_1}^{t_2} \frac{AET}{PET}\, dt\right) \tag{1}$$

Dry-matter yield for the entire growing period of a cultivar and for 1-day intervals can be formulated as:

$$\text{Yield (DM)} = \bar{m}d\ \frac{\bar{AET}}{\bar{PET}} \tag{2}$$

This differs slightly from de Wit's (1958) formula, $Y = m(T/E_o)$, yet at the same time confirms it, since AET and PET are substituted by transpiration T and pan evaporation E_o, respectively; the time factor or the duration d (in number of days) of the growing period is explained; $\bar{m}$ is then for AET = PET, the daily average DM rate that is determined by photo-

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Note: This is an edited translation of the original French paper immediately preceding.

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synthesis (in relation to radiation and temperature) and soil fertility.

The product $\bar{m}d$ therefore represents, for a particular year, the yield Y_o for the year when AET = PET. Hence

$$Y/\bar{m}d = Y/Y_o = \frac{\bar{AET}}{\bar{PET}} \quad (3)$$

Given that there is little variation in m from one year to another in the tropics (identical soil and plant density, and photosynthetic saturation due to light and temperature), the yield Y_o varies each year with d. In fact, the duration of a photosensitive cultivar, for instance, varies according to the planting date and hence the photoperiod. If d_o is the optimum duration for yield; the potential interannual yield is md_o. If this potential yield is 100, the variable relative duration is $\delta = d/d_o$ with $0 \leqslant \delta \leqslant 1$. Thus:

$$Y/100 = \delta \cdot \frac{\bar{AET}}{\bar{PET}} \quad (4)$$

It is supposed that there is a linear relation between yield Y and δ, the relative growing period, at least in the first approach.

But the duration of the different development phases of a plant do not vary in the same way; some may even remain constant. For example, in the case of three phases, when each phase is weighted by an exponent k_i according to the water requirements, the following equation is obtained:

$$Y/100 = \delta_1 \left(\frac{\bar{AET}}{\bar{PET}}\right)_1^{k_1} \cdot \delta_3 \left(\frac{\bar{AET}}{\bar{PET}}\right)_2^{k_2} \cdot \delta_3 \left(\frac{\bar{AET}}{\bar{PET}}\right)_3^{k_3} \quad (5)$$

or, more generally:

$$Y/100 = \prod_{i=1}^{P} \delta_i \left(\frac{\bar{AET}}{\bar{PET}}\right)_i^{k_i} \quad (6)$$

The k_i coefficients show, in relation to the water factor, the relative importance of each phase in determining yield (Jensen 1968). If $\bar{m}$ is supposed to remain almost constant in the tropics, this formula can be applied to any photosensitive or photoinsensitive cultivar, whether or not δ_i varies with photoperiod and/or temperature. For a photoinsensitive cultivar under optimum temperature conditions throughout the growing period, δ values are equal to 1. Hence, for a three-phase development:

$$Y/100 = \left(\frac{\bar{AET}}{\bar{PET}}\right)_1^{k_1} \cdot \left(\frac{\bar{AET}}{\bar{PET}}\right)_2^{k_2} \cdot \left(\frac{\bar{AET}}{\bar{PET}}\right)_3^{k_3} \quad (7)$$

This is Jensen's formula (1968), which is also applicable to a photosensitive cultivar that is sown every year on a fixed date, with δ_i equal to 1.

Three major development phases have been considered for sorghum and millet crops:

- The vegetative phase—from germination to floral initiation, of relative duration δ_1;
- The flowering phase—from floral initiation to fruit setting, of relative duration δ_2;
- The fruiting phase—from fruit setting to grain filling, of relative duration δ_3.

If the cultivar is completely photosensitive and there is little interannual fluctuation in temperature, the relative durations δ_2 and δ_3 may be equal to 1 (the time of occurrence of the second and third phases is almost fixed). The relative duration δ of the vegetative phase alone varies according to the planting date. If grain yield and not dry-matter production is considered and MET (maximum evapotranspiration) replaces PET, the following equation is obtained:

$$Y/100 = \delta_1 \left(\frac{\bar{AET}}{\bar{MET}}\right)_1^{k_1} \cdot \left(\frac{\bar{AET}}{\bar{MET}}\right)_2^{k_2} \cdot \left(\frac{\bar{AET}}{\bar{MET}}\right)_3^{k_3} \quad (8)$$

The optimum length of the vegetative phase can be deduced through field experiments or determined by the first possible planting date or inferred from the equations in Annexure 1.

In this paper, the completely photosensitive cultivars are discussed first, followed by photoinsensitive and relatively photosensitive cultivars.

Completely Photosensitive Cultivars

The duration and time of occurrence of the flowering and fruiting phases remain quite stable, provided that these sorghums and millets are sown within a certain time interval (up to 2 months). The duration d_1 of the vegetative phase alone varies according to the planting date. This duration (d_1) plays an important role in determining crop productivity.

Curtis (1968) has shown that the photosensitive sorghum varieties that are traditionally grown in Nigeria generally head towards the end of the heavy rains. This can be seen more clearly from the monthly average rainfall curve for a station that is intersected by the mean PET and PET/2 curves (Fig. 1). When the points of intersection of these curves are numbered from 1 to 4, it can be seen that these varieties head near intersection 3 and therefore flower between intersections 3 and 4.

The same phenomenon was observed for photosensitive millet samples collected from villages in Upper Volta by Clement et al. in 1976. These samples were sown on 1 July at ICRISAT Center, Kamboinsé, near Ouagadougou, and the female flowering dates were recorded. Figure 1 shows that the flowering dates of the samples collected near Ouahigouya (13°55'N) in the north, at Ougadougou (12° 21') in the center, and at Bobo-Dioulasso (11° 10') in the south, fall between intersections 3 and 4. At Kamboinsé, the female flowering dates generally occur between intersections 3 and 4, with a margin of 5 days more or less, depending on whether the station is further north or south of Kamboinsé.

Yield of a photosensitive millet variety (Sanio) from Bambey, Senegal, was highest in those years when the heading date (20 Sept) was almost fixed and near intersection 3 (Cochemé and Franquin 1967; Franquin 1969). The deviation of the variable date of this intersection and the date 20 September accounts for 55% of the variance in yield.

Cochemé and Franquin (1967), Franquin (1969), Curtis (1968), Kassam (1974), and Wien and Summerfield (1980), who reported the same kind of observations for photosensitive cowpeas, give the following explanation of the effect of the flowering date on yield in relation to the end of the rains. If the flowering date is very early, the grain is damaged by pests and diseases; with delayed flowering, the crop escapes the direct impact of the rains on the earhead, but grain filling and physiological maturity are incomplete due to lack of water for fruiting.

The local photosensitive varieties generally meet these contradictory requirements better than the more northern or southern varieties. Through natural selection, these sorghum and millet varieties have grown to adapt themselves to two extremes of the local environment—the direct impact of rain on the plant and inadequate water in the soil. This adaptation is related to their response to photoperiod and temperature, two factors that hardly change over the years at a local level. For any location, those cultivars should be grown whose flowering dates are compatible with water availability and pest incidence.

Fitting of Completely Photosensitive Cultivars

A completely photosensitive cultivar usually flowers on a fixed date (except for a very late planting), but the duration of the vegetative cycle (d) varies with the planting date. In fact, only the duration (d_1) of the vegetative phase fluctuates, while the flowering and fruiting phases (d_2 and d_3) remain practically constant in duration and time of occurrence. All other things being equal, crop production depends on duration d_1 of the vegetative phase and "relative" productivity (Y/100) on the relative duration δ_1 of this phase.

Based on equation 8, the position in time of such a completely photosensitive sorghum or millet cultivar is adjusted as in the following example:

- The duration of the flowering phase is constant (d_2 = 50 days) and fixed in time, from the second 10-day period in August to the third 10-day period in September; heading occurs in the second 10-day period of September (actual case at Ouagadougou).
- The duration of the fruiting phase, which follows the flowering phase, is constant (d_3 = 30 days) and fixed in time, and continues through October.
- The duration d_1 of the vegetative phase, which precedes the flowering phase, varies according to the planting date. This planting date is simulated at the beginning of each of the 50 annual water balances which are in turn simulated for 10-day intervals (Fig. 2). The 10-day period for planting is the first 10-day period when rainfall is usually equal to or higher than PET/2 (average 35 mm at Ougadougou). Under these conditions, the planting period extends over 2 months—from the first 10-day period of May (M1) to the first 10-day period of July (Jy1). The vegetative phase covers ten 10-day periods, from M1 to the second 10-day period of August; this is the optimum duration, d_o. The durations d_1 are related to this optimum duration, d_o = 10. Therefore, when the crop is sown in Jy1 the vegetative phase covers four 10-day periods; hence δ_1 = 0.4; if the 10-day period for planting is the first one in June (J1), d_1 is then equal to seven 10-day periods, hence δ_1 = 0.7; and so on.

The water balances were calculated on the basis

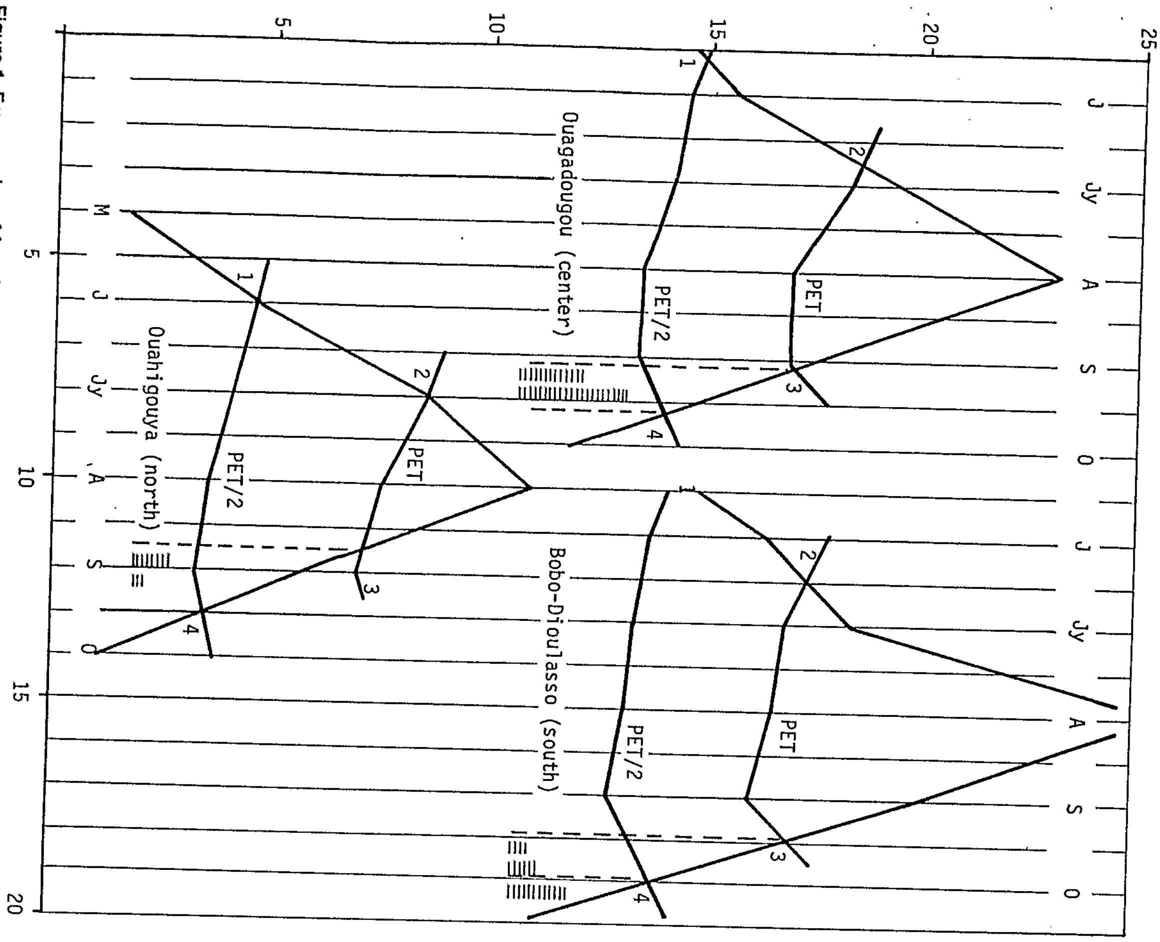

Figure 1. Frequencies of female flowering dates at the Kamboinsé station (near Ouagadougou) of millet samples collected in villages near Ouahigouya (north), Ouagadougou (center), Bobo-Dioulasso (south). The flowering dates fall between intersections 3 and 4 of the average monthly rainfall curves and PET and PET/2 curves. At Bobo-Dioulasso, millets flower earlier than at Kamboinsé and at Ouahigouya, a little later.

	Period		P	HD	HR	PET	K	MET	AET	RS	RDR	RDRC	D(RS)	MET-AET/ MET	AET/PET	MET-AET	AWC
1	January	1st	0.0	0.0	0.0	54.0	0.50	27.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	27.0	0.0
2	January	2nd	0.0	0.0	0.0	56.0	0.50	28.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	28.0	0.0
3	January	3rd	0.0	0.0	0.0	56.1	0.50	28.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	28.0	0.0
4	February	1st	0.0	0.0	0.0	62.0	0.50	31.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	31.0	0.0
5	February	2nd	0.5	0.5	1.00	63.0	0.50	31.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	31.5	0.5
6	February	3rd	0.0	0.5	1.00	57.6	0.50	28.8	0.0	0.5	0.0	0.0	0.0	1.00	0.0	28.8	0.5
7	March	1st	0.0	0.5	1.00	67.0	0.50	33.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	33.5	0.5
8	March	2nd	0.0	0.5	1.00	69.0	0.50	34.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	34.5	0.5
9	March	3rd	0.0	0.5	1.00	71.5	0.50	35.7	0.0	0.5	0.0	0.0	0.0	1.00	0.0	35.7	0.5
10	April	1st	0.0	0.5	1.00	71.0	0.50	35.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	35.5	0.5
11	April	2nd	0.4	0.9	1.00	71.0	0.50	35.5	0.0	0.9	0.0	0.0	0.0	1.00	0.0	35.5	0.9
12	April	3rd	5.0	5.9	1.00	71.0	0.50	35.5	5.9	0.0	0.0	0.0	5.9	0.83	0.08	29.6	5.9
13	May	1st	20.8	20.8	1.00	70.0	0.50	35.0	20.8	0.0	0.0	0.0	20.8	0.41	0.30	14.2	20.8
14	May	2nd	44.0	44.0	1.00	69.0	0.50	34.5	34.5	9.5	0.0	0.0	34.5	0.0	0.50	0.0	44.0
15	May	3rd	47.8	50.0	1.00	72.6	0.50	36.3	36.3	13.7	7.3	7.3	36.3	0.0	0.50	0.0	50.0
16	June	1st	25.7	39.4	0.79	64.0	0.55	35.2	35.2	4.2	0.0	7.3	45.8	0.0	0.55	0.0	50.0
17	June	2nd	69.9	50.0	1.00	60.0	0.65	39.0	39.0	11.0	23.8	31.1	39.0	0.0	0.65	0.0	50.0
18	June	3rd	24.0	35.0	0.70	58.0	0.80	46.4	35.0	0.0	0.0	31.1	50.0	0.25	0.60	11.4	50.0
19	July	1st	38.5	38.5	0.77	56.0	1.00	56.0	38.5	0.0	0.0	31.1	50.0	0.31	0.69	17.5	50.0
20	July	2nd	50.6	50.0	1.00	55.0	1.10	60.5	50.0	0.0	0.6	31.7	50.0	0.17	0.91	10.5	50.0
21	July	3rd	23.1	23.1	0.46	56.1	1.10	61.7	23.1	0.0	0.0	31.7	50.0	0.63	0.41	38.6	50.0
22	August	1st	158.0	50.0	1.00	47.0	1.10	51.7	50.0	0.0	108.0	139.7	50.0	0.03	1.06	1.7	50.0
23	August	2nd	176.1	50.0	1.00	45.0	1.10	49.5	49.5	0.5	261.1	265.8	49.5	0.0	1.10	0.0	50.0
24	August	3rd	88.9	50.0	1.00	49.5	1.10	54.4	50.0	0.0	39.4	305.2	50.0	0.08	1.01	4.4	50.0
25	September	1st	36.9	36.9	0.74	46.0	1.10	50.6	36.9	0.0	0.0	305.2	50.0	0.27	0.80	13.7	50.0
26	September	2nd	30.4	30.4	0.61	48.0	1.10	52.8	30.4	0.0	0.0	305.2	50.0	0.42	0.63	22.4	50.0
27	September	3rd	20.8	20.8	0.42	50.0	1.10	55.0	20.8	0.0	0.0	305.2	50.0	0.62	0.42	34.2	50.0
28	October	1st	10.3	10.3	0.21	56.0	0.90	50.4	10.3	0.0	0.0	305.2	50.0	0.80	0.18	40.1	50.0
29	October	2nd	0.0	0.0	0.0	59.0	0.70	41.3	0.0	0.0	0.0	305.2	50.0	1.00	0.0	41.3	50.0
30	October	3rd	2.2	2.2	0.04	60.5	0.50	30.2	2.2	0.0	0.0	305.2	50.0	0.93	0.04	28.0	50.0
31	November	1st	0.0	0.0	0.0	56.0	0.50	28.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	28.0	50.0
32	November	2nd	0.0	0.0	0.0	57.0	0.50	28.5	0.0	0.0	0.0	305.2	50.0	1.00	0.0	28.5	50.0
33	November	3rd	0.0	0.0	0.0	54.0	0.50	27.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	27.0	50.0
34	December	1st	0.0	0.0	0.0	52.0	0.50	26.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	26.0	50.0
35	December	2nd	0.0	0.0	0.0	52.0	0.50	26.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	26.0	50.0
36	December	3rs	0.0	0.0	0.0	55.0	0.50	27.5	0.0	0.0	0.0	305.2	50.0	1.00	0.0	27.5	50.0
	Total		873.6			2116.9		1388.2	568.4							819.8	
	Average													0.66	0.29		

Figure 2. Example of a simulation of a 10-day water balance for a photosensitive sorghum or millet cultivar with almost fixed flowering date. The duration of the vegetative phase (in this case 90 days) varies with the sowing date; the duration and occurrence of the flowering (50 days) and fruiting (30 days) phases remain almost constant. The AET/PETand AET/MET values can be estimated from this simulation'

of available water capacity (AWC) of 50, 100, and 150 mm.

In the extreme case of a crop sown in M1, the sequence of the crop coefficient K related to the water balance is as follows; the brackets serve to mark off the phases:

(0.50-0.50-0.55-0.65-0.80-1.00-1.10 -1.10-1.10-1.10)
(1.10-1.10-1.10-1.10-1.10) (0.90-0.70-0.50)

In the other extreme case of a crop sown in Jy1, the sequence of K is as follows:

(0.50-0.50-0.55-0.65)
(0.80-1.00-1.10-1.10-1.10) (0.90-0.70-0.50).

Figure 2 shows an annual water balance established on these principles, with an AWC of 50 mm for the Ouagadougou station near Kamboinsé.

As millet or sorghum yields were not available, the coefficients obtained in an experiment conducted under irrigation by Jensen and Sletten (1965) are used here to calculate the k_1, k_2, and k_3 coefficients of equation 8, which are 0.5, 1.5, and 0.5, respectively. The next step is to calculate, for each of the 50 annual water balances based on three AWC values (50, 100, and 150 mm), the expression:

$$Y/100 = \delta_1 \left(\frac{\bar{AET}}{\bar{MET}}\right)_1^{0.5} \cdot \left(\frac{\bar{AET}}{\bar{MET}}\right)_2^{1.5} \cdot \left(\frac{\bar{AET}}{\bar{MET}}\right)_3^{0.5} \qquad (9)$$

The mean values, calculated over 50 years, of each of the three multiplicative terms of equation 9 and the mean values of Y/100 for each of the three AWC values are given in Figure 3. The frequency

Table 1. Frequency distributions of AWC/100 for three values of AWC.

Y/100	AWC: 50 mm	AWC: 100 mm	AWC: 150 mm
0.01-0.10	IIIIIIIII	II	
0.11-0.20	IIIIIIIIIIIII	IIIIII	IIII
0.21-0.30	IIIIIIIIIIIII	IIIIIIII	IIIII
0.31-0.40	IIIIII	IIIIIII	IIIIIIIIII
0.41-0.50	IIIII	IIIIIIIIIIIII	IIIIIIIIIII
0.51-0.60	II	IIIIII	IIIIIIIIIIIII
0.61-0.70		IIII	IIII
0.71-0.80		IIII	IIII
Mean	0.23	0.40	0.45

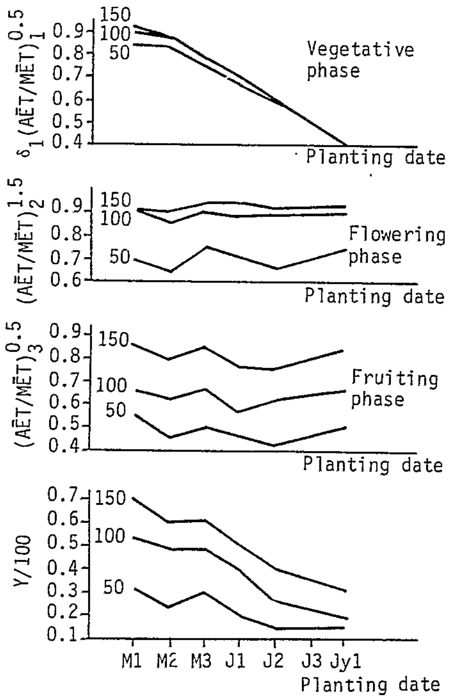

Figure 3. Variations in relative terms of yield corresponding to the vegetative, flowering, and fruiting phases according to AWC values (50, 100, 150 mm) and the sowing date. The combined variations in these terms bring about variations in relative yield (Y/100). δ_1 varies with the sowing date, from 0.4 (Jy1) to 1.0 (M1). Yield decreases with the sowing date (i.e. with δ_1) and increases with AWC (50, 100, 150 mm) for the flowering and fruiting phases.

distributions of AWC/100 for each of the three AWC values are compared in Table 1.

In Figure 4, the water deficits during the flowering and fruiting phases are seen through a frequency representation in time. These deficits, represented by the dotted areas in the figure, are bounded:

1. On the left, by continuous curves, obtained by applying the principle of the frequency period of vegetation (see Introduction) to the water balances. The curves at the bottom of the figure, related to the flowering phase, show the

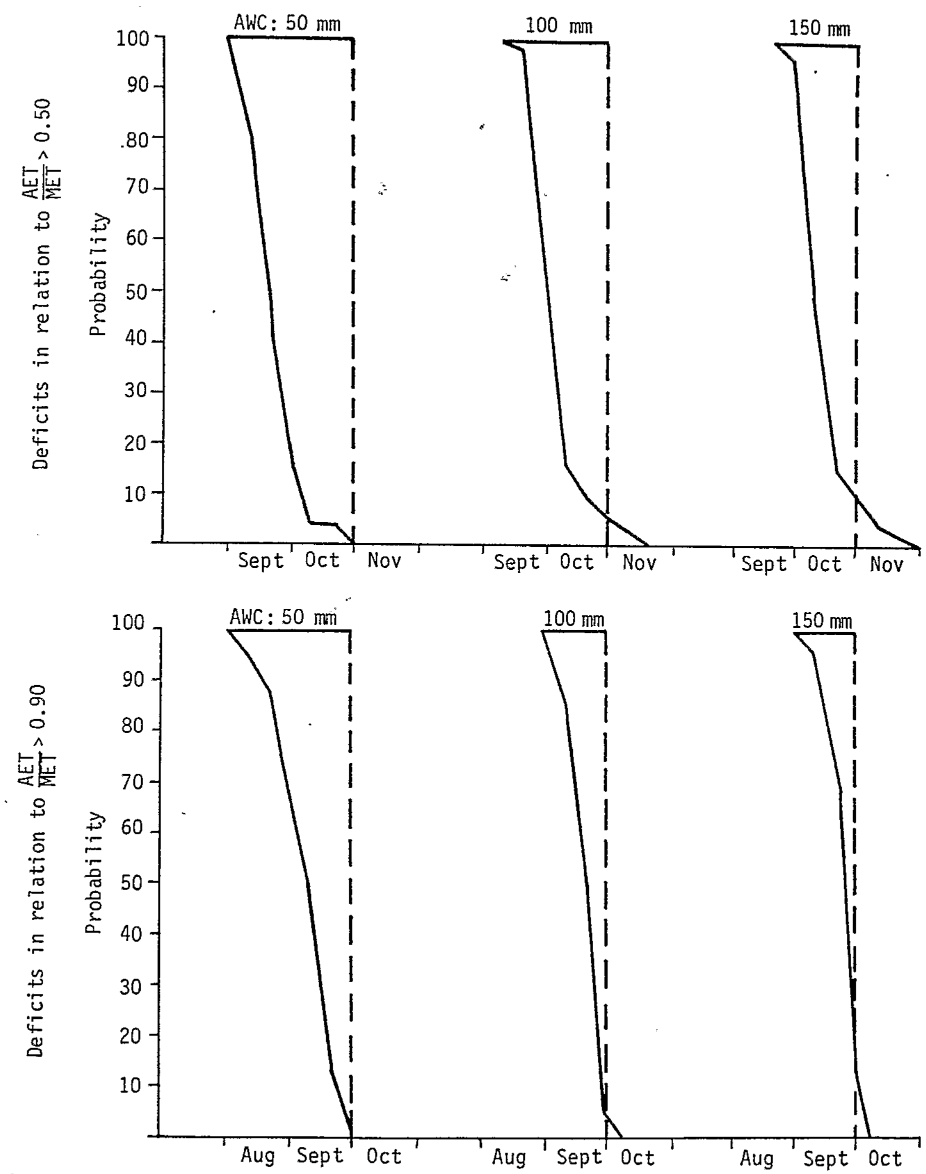

Figure 4. Representation in frequency and in time of water deficits according to AWC values of 50, 100, 150 mm: above, deficit in relation to AET/MET > 0.50 in the fruiting phase; below, deficit in relation to AET/MET > 0.90 in the flowering phase. The duration of the deficit is expressed in terms of probability, which decreases with the AWC.

observed probabilities of exceeding 0.90 AET/PET; the curves at the top related to the fruiting phase show the observed probabilities of exceeding 0.50 AET/PET; these AET/PET levels have been somewhat arbitrarily fixed to represent the minimum value required for adequate yields. However, it is possible to choose any other threshold values in the water balances.

2. On the right, by broken curves, corresponding to the 1.00 probability of exceeding the 0.90 and 0.50 threshold values on the last date of the flowering and fruiting phases.

Conclusion

It is quite clear that for a late-heading cultivar that avoids the impact of rainfall on the earhead, the water deficit during the flowering and fruiting phases would be much higher. However, this risk is reduced as the water-holding capacity of the soil increases.

Another alternative is to identify an early-heading cultivar with pest resistance for soils with a low water-holding capacity.

Remarks

The rate of increase of Y/100 (see the frequency distribution) is higher for 50 to 100 mm than for 100 to 150 mm for a cultivar that heads during the second 10-day period in September.

The water available during the vegetative phase always appears to be adequate, irrespective of AWC (Fig. 3) and the simulated planting date (first 10-day period with total rainfall exceeding PET/2 or an average of 35 mm at Ouagadougou). If this does not occur in reality, it is because water is lost through runoff and should be checked. A water balance calculated on the basis of 5-day intervals would probably reveal water deficits more frequently than one calculated on the basis of 10-day intervals. Excess rain during the vegetative phase may depress yields.

An early planting increases yields (Fig. 3), as it extends the duration of the vegetative phase. However, due to the low rainfall, there is no further increase if the crop is sown before the 10-day period M1, which marks the limit of the optimum duration d_o (ten 10-day periods for the vegetative phase).

Photoinsensitive and Relatively Photosensitive Cultivars

Expressed in terms of the "sum of degree-days," the duration of the completely photoinsensitive cultivars appears to be constant. Evaluated in terms of the "number of days," the duration remains constant if there is little variation in the night temperature, as during the rainy season.

As photoinsensitive cultivars are of short duration (70-80 days or even less), they do not have the same yield potential as the photosensitive cultivars whose vegetative phase can be extended. Photoinsensitive millets are found in northern Upper Volta where the growing season is very short, but they are also grown in the south in the region of Leo, for example, where they are used as a stop-gap crop.

Photoinsensitive cultivars are flexible, since their flowering date is not fixed, unlike completely photosensitive cultivars. This makes it easier to synchronize their flowering and fruiting phases with optimum moisture availability. They can also be sown at the beginning of the rainy season as a stop-gap crop. Their duration should be extended to 100 days, for example, to increase their yield potential.

The relatively (not completely) photosensitive cultivars are also useful, since their duration increases as the crop is sown earlier (but not too early). Like photoinsensitive cultivars, they have fixed flowering and fruiting dates only if their planting date remains fixed. When there is little variation in the planting date, the relatively photosensitive cultivars behave like the photoinsensitive cultivars.

Fitting of Photoinsensitive or Relatively Photosensitive Cultivars

The fitting of the flowering and fruiting phases is facilitated by using a model of the "frequency climatic period of vegetation." Such models were constructed for Ougadougou by simulating water balances (Fig. 2) based on an AWC of 50 (Fig. 5) and 100 mm (Fig. 6). The outer line represents the "semi-humid" subperiod determined by the probability that AET/PET is equal to or higher than 0.50. The inner line defines the "humid" subperiod determined by the probability that AET/PET is equal to or higher than 0.90.

If a photoinsensitive cultivar of 100 days, under

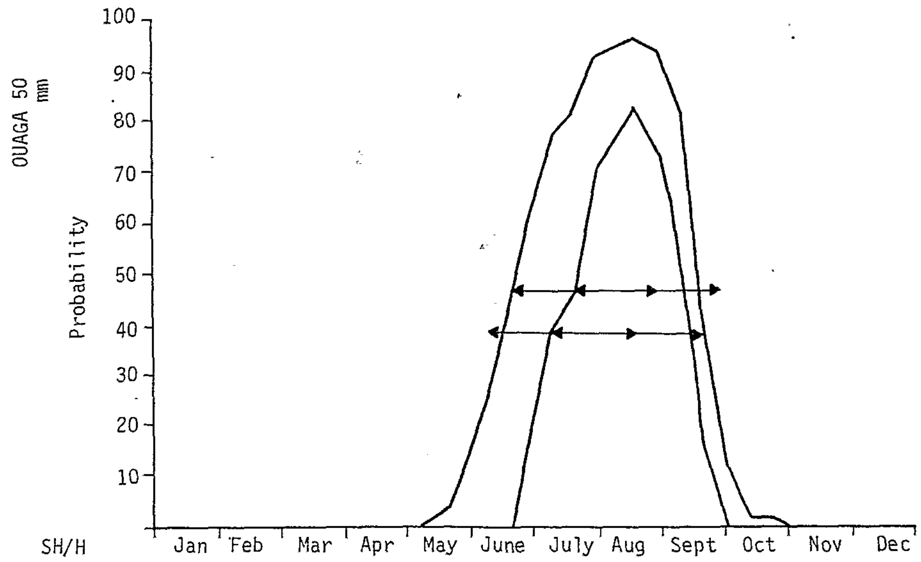

Figure 5. Fitting the flowering and fruiting phases of a 100-day sorghum or millet variety within the frequency "humid" (inner line) and "semi-humid" (outer line) subperiods at Ouagadougou. The humid subperiod is determined by the probability AET/MET > 0.90. The "semi-humid" subperiod is determined by the probability AET/MET >0.50. AWC is 50 mm: the favorable planting period is only 20 days (J2+J3) and the probabilities of fitting the flowering and fruiting phases do not exceed 0.38 and 0.42, respectively.

the temperature conditions at Ouagadougou, or a relatively photosensitive cultivar, also of 100 days, are sown on the same date, the duration and crop coefficients would be:

(0.50-0.55-0.60) (0.80-1.00-1.10-1.10) (0.90-0.70-0.50).

The flowering phase of 40 days is the most critical period for yield in relation to water availability. It should be fitted to the highest probability within the humid subperiod (Fig. 5 inner line). This probability is:

0.70 (on 1 Aug) x 0.54 (on 10 Sept) = 0.38

For this apparently optimum adjustment of the flowering phase, the cultivar should be sown in the first 10-day period of July (Jy1). But it is not possible to plant a cultivar during the same 10-day period each year. This interval should be made more flexible and increased to 20 to 30 days. If the flowering phase is moved back one, two, or three 10-day periods, corresponding to sowings in J3, J2, and J1, the probabilities of fitting the flowering phase would be 0.34, 0.31, and 0.12, respectively. Since the last probability is very low, the planting period would cover three 10-day intervals—J2+J3+Jy1. As the flowering phase would then coincide with maximum rainfall, the cultivars should also be resistant to pests and diseases.

The conditions for fitting the fruiting phase (30 days) also need to be examined in relation to probabilities associated with the "semi-humid" subperiod (the line on the right side of the outer curve, Fig. 5). For the fruiting phase, the probability of success is very low (on 10 Oct) for a sowing in Jy1; it is 0.12 (on 30 Sept) for a sowing in J3; and 0.42 (on 20 Sept) for a sowing in J2. Lastly, the appropriate interval for sowing is reduced to two 10-day periods: J2+J3.

This interval is essential for obtaining stable and high yields. If the planting date is simulated as in the case of a completely photosensitive cultivar (see

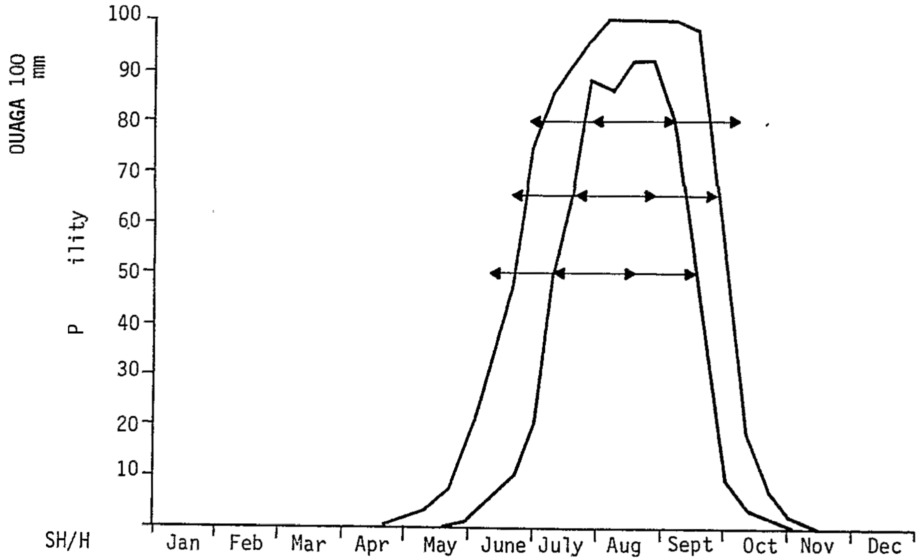

Figure 6. Same as Figure 5, but AWC = 100 mm: the planting period extends over 30 days(J2+J3+Jy1) and the probabilities of fitting the flowering and fruiting phases are 0.70 and 0.98, respectively.

earlier section), then the frequency distribution of Y/100 can be compared, using the formula

$$Y/100 = (\bar{AET}/\bar{MET})_1^{0.5} \cdot (\bar{AET}/\bar{PET})_2^{1.5} (\bar{AET}/\bar{PET})_3^{0.5} \qquad (10)$$

applied to the simulated water balances:

- for planting during the J2 10-day period;
- for any plantings from M1 to Jy1.

These frequency distributions are given in Table 2.

Table 2. Frequency distribution of relative yield for plantings in different 10-day periods.

Y/100	Any planting (M1-Jy2)	Planting in J2
0.21-0.30	II	
0.31-0.40	III	
0.41-0.50	IIII	
0.51-0.60	IIIII	
0.61-0.70	IIIIIIIIIII	IIIIII
0.71-0.80	IIIIIII	III
0.81-0.90	IIIIIIIIIII	IIIIIIIIIIIIIIIIIIIII
0.91-1.00	IIIIIII	IIIIIIIIIIIIIIIIIIII

If the same cultivars are grown on a soil with a moisture-retention capacity of not 50 mm but 100 mm, it is evident from Figure 6 that the interval suitable for planting increases from 20 to 30 days (J2+J3+Jy1) also considerably increasing the probabilities for fitting the flowering and fruiting phases.

Conclusion

A photoinsensitive or relatively photosensitive cultivar has greater flexibility for fitting than a completely photosensitive cultivar, particularly if it is grown on a soil with adequate water-holding capacity. However, this character must be combined with good pest resistance, since the flowering and fruiting phases are not fixed in time and may occur during the heavy-rainfall period.

Acknowledgment

I am grateful to Messrs. Clement, Perret, et al., who collected the millet samples from Upper Volta, and to the ICRISAT Upper Volta program for the observations on flowering of these samples.

Annexure

Length of the Vegetative Phase and Number of Internodes

In a completely photoinsensitive plant, the duration d of the vegetative phase depends solely on temperature, under light saturation conditions, according to the equation:

$$d(\bar{T}_i - T_o) \simeq \Sigma(T_i - T_o) = K \qquad (A1)$$

where T_i is the mean temperature (at night, for a short-day plant) on the day i; T_o, the base temperature and K, a constant for the variety.

In a completely photosensitive plant, the duration d is determined by both the photoperiod and temperature, according to the equation:

$$d(\bar{T}_i - T_o) \simeq \Sigma(T_i - T_o) \simeq k_o + \frac{\pi m}{2a} \left[1 + tg^2\left(\frac{\pi}{2}\ \frac{N_o/H_o}{\bar{N}_i/\bar{H}_i}\right)\right] \qquad (A2)$$

This result, for a short-day sorghum or millet plant, is based on the following principles. The plant is regulated by a circadian rhythm consisting of two periods of 24 h, one of daylight sensitivity of duration H_o, the other of darkness sensitivity of duration N_o ($H_o + N_o = 24$). The oscillations of the endogenous system N_o/H_o form the basis to which the exogenous oscillations N_i/H_i of actual day and night lengths are compared by means of the phytochrome. This information on the "imposed" fluctuation N_i/H_i (in relation to the "own" fluctuation N_o/H_o) can be effectively introduced in the differential equation of a forced harmonic oscillator set off by friction of day/night alternance:

$$u'' + \cot g^2\left(\frac{\pi}{2}\ \frac{N_o/H_o}{\bar{N}_i/\bar{H}_i}\right)u' + \left(\frac{\pi}{N_o/H_o}\right)^2 u = a(T_i - T_o)\frac{1}{\bar{N}_i/\bar{H}_i} \sin\left(\frac{\pi}{\bar{N}_i/\bar{H}_i} h\right) \qquad (A3)$$

The integration, in relation to h (h = t / [24-t], $0 \leqslant t \leqslant 24$) of heat excitation related to a ($T_i - T_o$)—excitation with a minimum threshold m for floral induction—leads to equation 2, in which a and m are parameters.

The number n of nodes or leaf internodes at floral initiation depends on the photoperiod and temperature according to the equations:

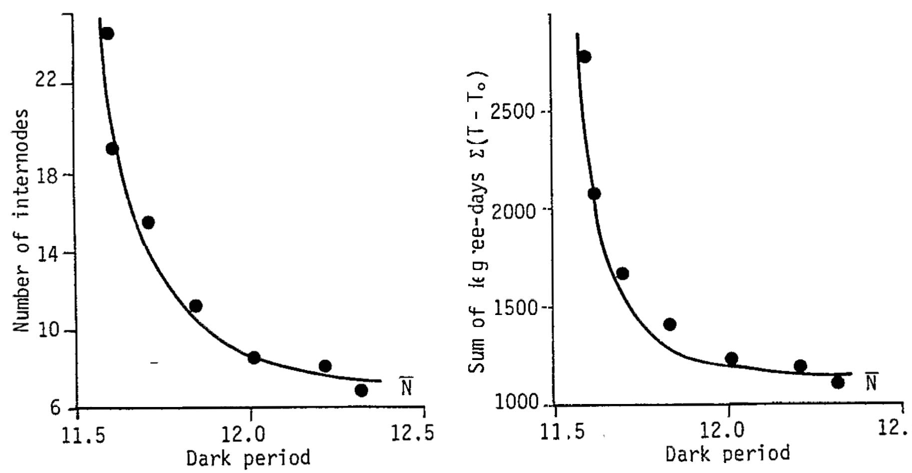

Figure 7. Data on a sorghum variety grown in Chad in farmers' fields. Right: fitting of equation A2 in Annexure 1 to the sum of degree-days Σ (T_i-T_o) according to the average dark period $\bar{N}_i$; left: fitting of equation 4 to the number of stem nodes according to the average dark period $\bar{N}_i$.

$$n = n_\circ + \alpha m t g^2 \left(\frac{\pi}{2} \frac{N_\circ/H_\circ}{\bar{N}_i/\bar{H}_i}\right) \quad (A4)$$

$$n = n_\circ + \alpha \frac{2a}{\pi} \sin^2 \left(\frac{\pi}{2} \frac{N_\circ/H_\circ}{\bar{N}_i/\bar{H}_i}\right) \Sigma \; (T_i - T_\circ) \quad (A5)$$

where $k_\circ$ represents the sum of temperatures and $n_\circ$ the total number of nodes in the "juvenile" phase; $\pi m/2a$ can be reduced to a single parameter, k; thus $k_\circ + k = K$, k being the sum of temperatures between two nodes.

These equations have been confirmed for sorghum cultivars, as can be seen from the statistical fitting of equations 2 and 4 (Fig. 7).

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